# Improved Techniques for Targeting Additional Observations to Improve Forecast Skill

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**LONG-TERM GOAL**

This project aims at studying advanced targeting techniques to improve weather forecast skill and address the question of the optimization of composite observing systems with adaptive components.

**OBJECTIVES**

In numerical weather prediction (NWP) the computational representation of the atmosphere produces unavoidable uncertainties in both the equations of motion (model error) and the initial state (initial error).

These limitations imply forecast errors and uncertainty. Observation targeting aims at better describing the initial state, by using additional observations. The targeted locations are chosen beforehand such that they fall in regions for which a given forecast is sensitive. See Joly (2002) for a overview of the principles of observation targeting and its philosophy. The so-called sensitive regions where to deploy supplementary observations can be computed with several objective techniques. In this work, the computation of sensitive regions is done with the adjoint technique and uses the singular vectors of the propagator of the tangent-linear forecast model (Palmer *et al.*, 1998).

Observation targeting has been implemented in several field experiments since 1997. The objective techniques used singular vectors and other adjoint based methods, or ensemble based approaches. Following FASTEX in 1997, adaptive observations have been deployed each winter over the Northern Pacific during the campaigns NORPEX and WSRP (Szunyogh, 2000). It has been verified that the deployment of additional adaptive observations and their assimilation improve the forecasts, on average. However, strong variability among the cases were detected. To make the adaptive observa-

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tions more efficient, the newly developed targeting techniques had to be optimized. Hence, it has been shown that the impact of targeting depends on assimilation scheme used (Bergot, 2001). In spite of several years of practice, the spatial distribution of additional observations are still subjectively chosen, but it is now possible to estimate which deployment, among alternative ones within the sensitive region, is expected to have the highest impact on the subsequent forecast. Thus the most advanced targeting techniques estimate the variance of the forecast errors and its reduction when the forecasts are improved. Moreover, the development of targeting techniques is among the main objectives of the program THORPEX (Shapiro, 2003). The THORPEX Observing System Test (TOST) over the Atlantic ocean to be implemented during the Autumn 2003, will offer an opportunity to employ and compare newly developed targeting techniques.

One objective of this work has been to develop a real-time tool to produce a targeting guidance for the TOST 2003, which involves the latest techniques based on the adjoint model.

**APPROACH**

The technique used in this project considers an estimate of forecast error variance and its decrease when the observation network is enhanced with additional observations. To do this, the evolution of error is assumed tangent-linear and the contribution of model errors to the forecast error is neglected. With an adequate initial metric, that is an estimate of the initial uncertainty, the leading singular vectors of the tangent-linear model span a subspace that accounts for most of the variance of the forecast errors at the verification time. The metric used is the Hessian (second derivative) of the so-called cost-function of the 4D-Var data assimilation scheme (Palmer *et al.*, 1998; Barkmeijer *et al.* 1999). Hence, the singular vectors are called Hessian singular vectors and they infer a distribution of initial errors that is consistent with the underlying statistics of the assimilation scheme. This distribution of initial errors is inhomogeneous and includes multivariate and spatial correlations. One can base a targeting technique on such vectors, and thus can hope to achieve a good level of optimization of this technique. Hessian Reduced Rank Estimate is the name that depicts the properties of this technique (noted HRRE hereafter).

The HRRE estimates the reduction of the forecast error variance in two steps. First, an estimate of the uncertainty pertaining to the routine observing network is required. This is done through the computation of Hessian singular vectors, that determine a sensitive region. Second, the reduction of the uncertainty resulting from the assimilation of additional observations is computed with respect to the initial value. Thus, the prediction of the reduced variance of errors is consistent with the underlying statistics of the assimilation scheme. By reducing the forecast error variance, it is expected to reduce forecast error itself, on average.

The underlying statistical framework of this approach also allows one to study some other questions about the optimization of composite observing systems. As a complement of classical OSEs, the HRRE can help us to evaluate whether targeting with in-situ observations is still worth while in the perspective of a future observing network where satellite soundings will take a more and more important part. Therefore, a further objective of this work is to investigate the question of whether in-situ observations are still being needed to efficiently constrain forecast errors, in some cloudy sensitive areas where the future satellite data will still be cloud contaminated.

To quantify the forecast error variance, the Integrated Forecast System (IFS) needs the observations

to be processed like in an assimilation task (calculation of the 4D-Var objective function and of its Hessian). The targeting guidance can be either in the form of sensitivity maps made with the Hessian singular vectors or an estimate of the reduction of the variance due to any additional observation set. Though the Hessian maps look similar to the FASTEX-like sensitivity maps built on Total Energy singular vectors, the Hessian sensitivity maps account for the observation coverage and the accompanying data assimilation system.

Whatever its form, a targeting guidance has to be delivered sufficiently in advance, in order to leave enough time to deploy the observing platforms at the right place before the measurements have to be taken. It must be computed beforehand, that is, before the routine observations that enter the Hessian SV have actually been taken. To make the HRRE be a real-time targeting tool, the Hessian singular vectors have to be predicted. This implies that either the initial metric itself must be predicted or the routine observation coverage must be predicted. Once the singular vectors have been predicted, the HRRE uses only simulated observations and this calculation does not depend on real-time.

The most straightforward way to predict Hessian singular vectors is to assume that the routine observation coverage is present on the date of the targeted observation deployment. As the relevant statistical information is the distribution in space and time of the observations and the variance of their errors, rather than the observed values themselves, we can use a forecast to simulate those values as well. Most of the in-situ routine network is stable in time. As a consequence, the expected routine in-situ observation coverage in some near future should be close to the present one (or short past one). But some remote sensed observations have their geographical position linked to the clouds whose position is hard to predict. Thus the location of observations such as the infra-red satellite soundings and the wind data derived from cloud motion would face major errors. Therefore, it is important to know what is the influence of such observation types on the Hessian singular vectors set.

## WORK COMPLETED

For the TOST 2003, ECMWF is preparing a panel of adjoint-based targeting guidance; one of the scientific objectives of the TOST is to evaluate how well the different targeting techniques available today perform in reality. A comprehensive set of sensitive areas based on total energy optimized singular vectors will be produced daily for 3 fixed verification areas and 3 forecast ranges. A higher resolution set of singular vector with moist physics in the tangent linear model will be optimized on the request from the TOST Operation Center, where the targeting decisions will be taken. Both techniques can be considered as FASTEX-like techniques, that only account for the dynamics (and the physics) of the atmosphere. The most advanced targeting guidance will be based on the predicted Hessian singular vectors without any cloud-location-sensitive observations in their metric. The optimization time and verification region will be on demand from the TOST Operation Center. According to the theory and some experimental results (Leutbecher, 2002), the last technique is expected to perform better than the use of Total Energy singular vectors.

Investigation dealing with the comparison of high resolution satellite data with in-situ ones is motivated by the idea that in spite of their very high geographical density, their vertical resolution and their small measurement errors, the future infra-red satellite sounders may still poorly describe the cloud covered sensitive regions of the atmosphere (such sensitive regions are likely to be over ocean). The approach can use the HRRE in order to avoid long series of analysis/forecast experiments. The respective expected benefit of each type of observation can be estimated. However, a real OSE using

realistically simulated satellite and in-situ data is still needed as a validation of the HRRE. Indeed, the magnitude of the forecast error variances estimated with the HRRE technique must still be verified. It must be stressed however that all those experiments assume a fixed distribution of the background forecast errors and that modifications of the observing network are limited in space and time. This assumption may not hold especially with the large sample of satellite profiles that would be assimilated daily in practice and would influence the statistics of the background. In that sense, such a study is not truly an OSE.

**RESULTS**

Unlike the HRRE, the Ensemble Transform Kalman Filter (ETKF) has been used for several years as a tool for the targeting campaigns in the Pacific Ocean. Such an algorithm is based on an ensemble and but does not rely on the operational assimilation scheme. But both algorithms yield similar targeting guidance, in terms of either sensitivity or signal maps and ranking of some possible adaptive deployments. The ETKF will be available at UK Met Office during the TOST. Thus TOST is a unique opportunity to compare those two approaches in a real-time context.

With the HRRE, the signal maps can be computed for several observation types. The targeting guidance is then flexible and adapted to the observation strategy (soundings or single level aircraft observations). However, sensitive areas which depict a linear combination of vertical integration of the Hessian singular vectors show very similar patterns. As a consequence the main targeting guidance for the TOST to be produced with the HRRE will be sensitivity maps. If there will be some opportunity to compute a ranking of deployments for a research aircraft, the HRRE may be able to yields another kind of targeting guidance.

When predicting Hessian singular vectors, we need additional hypotheses to ensure their reliability. First, we have to suppose that the future network is like the one from the day we choose to be the reference one. That's the case for the ground-based observing system. Based on results from a (few) case studies, we found that the subspace spanned by Hessian singular vectors is not too sensitive to the removal of cloud-sensitive satellite observations in the initial metric.

In addition, the singular vector prediction is done along a trajectory which does not start from an analysis but from a 2 or 3 days forecast. We have verified that this use of the forecast trajectory does not really matter for the singular vectors, unless the trajectory undergoes a major forecast failure. In such a case, the errors in the trajectory may lead to some change in the singular vectors.

We checked the consistency of the subspace spanned by the singular vectors with or without satellite data. The main changes occur in the upper part of the atmosphere, and are more noticeable on secondary networks (06 and 18Z). Considering the vertical structure of the Hessian singular vectors, the presence of satellite data constrains them to the troposphere. In the horizontal, the effect of the satellite data is mainly linked to the occurrence of some overlap of the sensitive region with the remotely observed area. If the verification region is quite small and less stretched than the area observed, no noticeable change is expected in the shape of sensitive areas. Some variation of the magnitude of the variances linked to the routine observations is likely to occur, but it should not affect the targeting guidance. However, in a given time window of a few hours, the orbiting satellite observation coverage corresponds to few paths across the area where the sensitive area is likely to occur. In such a case, some edge effect may affect the shape of of the sensitive area. But the presence

(or absence) of other data types like the aircraft data and the radio-soundings has a much more dramatic effect in that respect.

On the side of the comparison of in-situ with satellite data, some preliminary results have been obtained, showing a precedence of the in-situ observations on the satellite ones. But these have been done with infrared channels of NOAA16. We expect more mixed results with AIRS data.

## IMPACT/APPLICATIONS

The Atlantic TOST 2003 is the first real-time test of targeting techniques involving plenty of adaptable components of the routine network. Hence, change in the ship and land radio-sounding frequency or the activation of some commercial aircrafts will be part of the adaptive observation practice with some more targeting dedicated research aircrafts dropping sondes. With its ability to realistically account for the possible variability of the adaptive observation type, the HRRE could be a leading targeting technique in the future. Indeed, if successful, the TOST will be the starting point of a new way of managing the European Composite Observing System (EUCOS), with an adaptive dimension for which HRRE may play an important role. In addition, research in the domain of targeting for the next 10 years will take place in the perspective of THORPEX: targeting and observing system optimization are among THORPEX scientific objectives.

In conclusion, it is worth stressing the following remarks. The HRRE has the potential advantage of consistency with the underlying statistics of an operational assimilation scheme. The Ensemble Transform Kalman filter technique applied to a set of evolved ensemble perturbations may lack this consistency. Both techniques quantify the expected reduction of the forecast error variance implied by the addition of supplementary observations, but the HRRE uses quasi-realistic simulated observations to be processed with the operational assimilation observation operator. Thus many combinations of observation types can be considered. However, the verification of such quantities requires a long series of analysis/forecasts experiments on different meteorological cases. It is unlikely that a unique targeting campaign can generate enough data to enable such a verification process. Moreover, without alternative sets of observations being taken in reality, the estimate of ranking of the alternative deployments according to their expected benefit on the forecast quality cannot be verified. One could use simulated data as a first step towards such a verification, but real data remains essential : all targeted data from previous campaigns have to be used for that purpose. Finally, any improvement in the description of the statistics involved in the data assimilation and subsequently in the computation of the Hessian singular vectors would benefit this improvement. Especially, introduction of flow-dependent estimates of the background error covariances in the assimilation scheme, is expected to have a significant impact. Thus, ensemble based techniques (like ETKF) may have an advantage in that respect.

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